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Thesis Book

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NEURAL NETWORK-BASED MODELING OF VEHICLE DYNAMICS PARAMETERS FOR SAFETY-CRITICAL AUTOMOTIVE APPLICATIONS

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1 Introduction

The automotive landscape is undergoing a profound transformation, characterized by the ascendancy of software-defined vehicles (SDVs) over conventional mechanical systems. This paradigm shift results in increasingly sophisticated, software-centric architectures that govern a wide array of vehicle functions, from driver assistance and infotainment to indispensable safety features, thereby paving the way for interconnected and autonomous mobility solutions [1]. This technological progression is further propelled by key industry trends, notably vehicle electrification [2], alongside continuous innovations in vehicle dynamics. These innovations encompass advanced powertrain designs, adaptive suspension technologies, and refined chassis control mechanisms, all collectively striving to elevate vehicle stability, safety, and overall performance [3].

Integral to these advancements are electric brake systems, which deliver the precise and dependable braking performance essential for contemporary vehicle dynamics and the efficacy of safety-critical functions [4]. Such systems form the backbone of widely adopted safety features like Anti-lock Braking Systems (ABS), Electronic Stability Control (ESC), and a growing suite of Advanced Driver-Assistance Systems (ADAS) [5]. The operational integrity of these systems is critically dependent on a continuous stream of accurate, real-time sensor data. Signals detailing longitudinal and lateral accelerations, yaw and roll rates, individual wheel speeds, and the steering angle of the front axle provide the foundational information required for these complex systems to react appropriately to dynamic driving conditions. Consequently, ensuring the reliability and accuracy of these input signals is of paramount importance. This necessitates robust mechanisms for signal plausibility monitoring and underscores the growing significance of virtual sensor technologies, which can augment physical sensors, enhance system redundancy, and ensure continued functionality even in the event of partial sensor failure [6].

The accurate real-time estimation and short-term prediction of key vehicle dynamics parameters are thus fundamental to the effective operation of modern automotive safety and control systems. These parameters, including accelerations and rotational rates, are vital for maintaining vehicle stability, enabling precise trajectory planning for autonomous vehicles [7], and ensuring the effectiveness of active safety interventions such as Active Rollover Protection (ARP) [8].

However, the traditional approaches to obtaining these critical signals, often relying on empirical mathematical models, face considerable hurdles. These methods typically demand extensive and meticulous calibration tailored to specific vehicle configurations, requiring detailed knowledge of parameters such as mass distribution and suspension characteristics [9]. Such detailed information is often unavailable or subject to change during the early phases of vehicle development. While cutting-edge Artificial Intelligence (AI) paradigms have demonstrated impressive predictive prowess, their substantial computational and memory footprints often render them impractical for direct deployment within the resource-constrained embedded hardware prevalent in automotive ECUs and sensor modules [10].

Therefore, there exists a pressing and persistent need for advanced methodologies that can provide highly accurate and reliable estimations and short-term predictions of these vital vehicle dynamics parameters. Such methodologies must not only achieve high fidelity but also operate efficiently within the computational limitations of existing automotive hardware. The development of such robust and resource-efficient predictive capabilities is indispensable for the continued advancement of vehicle safety, the enhancement of

stability control systems, and the realization of more sophisticated autonomous driving functionalities.

2 Goals and applied methods

The primary goal of this research was to develop and validate robust, computationally efficient Artificial Neural Network (ANN)-based models capable of accurately estimating current values and forecasting future states of critical vehicle dynamics parameters. These parameters, including longitudinal and lateral accelerations, as well as yaw and roll rates, are fundamental inputs for advanced electric brake systems and other safety-critical automotive functions [11, 12]. A key objective was to design these models for seamless integration into resource-constrained embedded systems, such as Electronic Control Units (ECUs) or even directly within sensor hardware, utilizing only standard sensor signals readily available in modern vehicles [13]. This approach aims to enhance the predictive capabilities of vehicle control systems without necessitating vehicle-specific recalibration or specialized, costly sensor arrays, thereby ensuring broad applicability across diverse vehicle platforms and driving conditions, from urban environments to challenging off-road scenarios.

A cornerstone of this research was the collection and meticulous preparation of extensive experimental data, gathered using a commercial 2022 Sport Utility Vehicle (SUV) with maneuvers executed by professional test drivers across a wide spectrum of conditions. The test locations included the Continental proving ground in Veszprém, Hungary for controlled track scenarios; urban traffic within the city of Veszprém for real-world driving; and a dedicated off-road course in Brimley, Michigan, USA. During these tests, critical signals—including the four individual wheel speeds, the front axle steering angle, longitudinal and lateral accelerations, and the vehicle’s yaw and roll rates—were captured at a high sampling frequency of 100 Hz. The raw data subsequently underwent a systematic preprocessing workflow, including cleaning (e.g., removal of standstill data) and normalization based on expert-defined physical limits, to ensure high quality and suitability for model development. Emphasizing the principles of Open Science and to foster reproducibility and further research within the community, these curated experimental datasets, encompassing a rich variety of vehicle dynamic behaviors (e.g., calm, aggressive, city driving) and totaling significant recording hours, have been made publicly available [14], providing a valuable resource for researchers and engineers working on data-driven vehicle dynamics modeling and control.

To achieve the outlined goals, various methodologies were employed throughout this work. The core of the development involved the design and optimization of different neural network architectures:

- Lightweight feedforward neural networks were developed for tasks such as real-time lateral acceleration estimation, specifically optimized for minimal computational overhead, making them suitable for direct sensor-level integration [15].
- Long Short-Term Memory (LSTM) networks were extensively utilized for forecasting tasks, including the prediction of longitudinal acceleration [16], yaw rate [17], and roll rate [18], due to their inherent capability to capture temporal dependencies in time-series data.
- The predictive accuracy and computational demands of the proposed models were

rigorously benchmarked against existing approaches found in the relevant scientific literature, where applicable, demonstrating superior performance with significantly lower resource requirements.

- Comprehensive sensitivity analyses were conducted, particularly for the yaw rate prediction model, to assess its robustness against variations in operational conditions such as tire pressure, passenger load distribution, and differing vehicle body structures [19].

These methods collectively aimed to produce highly accurate, reliable, and deployable predictive models for enhancing vehicle safety and performance.

3 New scientific results

Neural Network-Based Prediction of Vehicle Accelerations

Thesis 1.1

I developed and optimized a resource-efficient feedforward neural network with a single hidden layer comprising five neurons, capable of accurately predicting lateral acceleration of vehicles based on standard vehicle sensor signals. The network was trained, validated, and tested exclusively using experimental data. The model utilizes inputs: wheel speeds, the steering angle of the front axle, and longitudinal acceleration. Achieving an R^2 exceeding 0.97 and a Mean Absolute Error (MAE) for the test set of 0.0172 g, the developed model demonstrates high accuracy. Due to its minimal computational demands, it is highly suitable for direct integration into vehicle sensors or the electronic brake system, functioning as a reliable virtual sensor.

Thesis 1.2

I developed and optimized a resource-efficient Long Short-Term Memory (LSTM) neural network that predicts future longitudinal acceleration values up to 100 milliseconds ahead with high accuracy by processing the historical sensor signals. The model achieves an R^2 value above 0.97 and a MAE of 5.30×10^{-3} g, even when predicting 100 ms into the future. Despite containing only a single hidden layer with five LSTM neurons, the network significantly outperforms existing approaches that rely on much larger architectures and considerably higher computational requirements. The model's development relied exclusively on experimental data, which was used throughout the training, validation, and testing phases to ensure its reliability under real-world conditions.

LSTM-Based Forecasting and Sensitivity Analysis of Yaw and Roll Rates in Automotive Systems

Thesis 2.1

I have developed an LSTM neural network optimized for forecasting vehicle yaw rate up to 200 ms ahead. The model is designed for broad applicability, utilizing only standard sensor signals - longitudinal/lateral acceleration, yaw rate, steering angle of the front axle, and wheel speeds - which are commonly found in vehicle electronic brake systems, thereby

eliminating the need for vehicle-specific parameters. The model, featuring a single hidden layer with 5 LSTM neurons, achieved exceptional performance on an independent test set: $R^2 = 0.9984$, $MAE = 0.316$ °/s, demonstrating high accuracy and efficiency for real-time deployment.

Thesis 2.2

I designed, trained, and validated a novel LSTM-based model for forecasting vehicle roll rate, specifically tailored for complex off-road driving conditions. After investigating various prediction horizons, I selected 40 ms ahead as an optimal timeframe. This choice balances declining prediction accuracy over longer horizons with the practical needs of safety-critical functions like ARP, providing valuable insight into immediate control effects while ensuring the model's output remains within ASIL B safety limits. The model, featuring a single hidden layer with 7 LSTM neurons, achieved $R^2 = 0.9593$, $MAE = 1.107$ °/s on an independent test set, demonstrating robust performance for off-road applications.

Thesis 2.3

I conducted a sensitivity analysis that confirmed the yaw rate prediction model's robustness against operational variations. Tests involving reduced tire pressure and varying passenger loads had minimal impact on prediction accuracy, with maximum Mean Absolute Error (MAE) deviations remaining below 0.5 °/s, even during aggressive driving where the effects were most noticeable. Furthermore, transferability tests across different vehicle types also yielded MAE deviations under 0.5 °/s, suggesting that vehicle weight distribution is more critical than overall mass, especially for hybrid and electric vehicles. Building on this demonstrated resilience, an investigation into training data volume established a practical guideline: based on the extensive experimental data collected for this study, 10-15 minutes of diverse, dynamic driving data provides sufficient accuracy for non-safety-critical applications. For safety-critical systems, however, the complete dataset is required to ensure maximum model robustness.

4 Utilisation of results

The research presented in this dissertation has led to the development of resource-efficient, high-accuracy neural network models for predicting critical vehicle dynamics parameters. These models have significant practical applications in enhancing automotive safety and performance.

The developed neural network architectures can accurately predict lateral and longitudinal acceleration, yaw rate, and roll rate using standard vehicle sensor inputs. These predictions are crucial for improving the functionality of safety-critical systems.

A key outcome is a compact feedforward neural network for lateral acceleration estimation, designed for such efficiency that it can be deployed directly within sensor hardware, effectively creating a virtual sensor. Furthermore, Long Short-Term Memory networks were developed to forecast future values of longitudinal acceleration (0.1 s ahead), yaw rate (0.2 s ahead) - whose robustness was confirmed through rigorous sensitivity analyses against variations in tire pressure, passenger load, and vehicle structure to meet safety standards - and roll rate in off-road conditions (0.04 s ahead). These forecasting

capabilities are directly applicable to enhancing the proactive response of brake control systems.

The models developed demonstrate superior accuracy compared to existing literature solutions while imposing significantly lower computational demands. This makes them highly suitable for deployment in embedded automotive systems with limited processing power.

The validation on extensive experimental datasets underpins their reliability for real-world deployment. The adaptability and efficiency of these models also position them as valuable tools for future integration into autonomous driving systems, contributing to the ongoing advancement of vehicle safety and stability. However, it is crucial to acknowledge that the models' validity is currently confined to the specific conditions under which they were tested, including speed ranges (up to 135 km/h for lateral acceleration, 50 km/h for yaw/longitudinal acceleration, and 30 km/h for the off-road roll rate model), high-friction surfaces for the on-road tests while the roll rate model was evaluated on off-road terrain, and a primary vehicle type (SUV), necessitating further validation for broader safety-critical deployment.

Publications

Data Used for Model Development

- P1** János Kontos, László Bódis and Ágnes Vathy-Fogarassy (2025). Experimental Sensor Data from Vehicles for Dynamic Vehicle Models [Dataset]. figshare. <https://doi.org/10.6084/m9.figshare.28078274.v1>

Neural Network-Based Prediction of Vehicle Accelerations

- P2** János Kontos, Balázs Kráncz and Ágnes Vathy-Fogarassy (2022). Neural network-based prediction for lateral acceleration of vehicles. *2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS)*, 153–158. Debrecen, Hungary. <https://doi.org/10.1109/CITDS54976.2022.9914270>
- P3** János Kontos, László Bódis, Ágnes Vathy-Fogarassy (2024). Forecasting longitudinal acceleration in urban vehicles. In I. Maglogiannis, L. Iliadis, J. Macintyre, M. Avlonitis, & A. Papaleonidas (Eds.), *Artificial intelligence applications and innovations* (Q3), (Vol. 713, pp. 85-98). Springer. https://doi.org/10.1007/978-3-031-63219-8_7
- P4** János Kontos, Ágnes Vathy-Fogarassy and Balázs Kráncz (2021). Phase plane-based approaches for event detection and plausibility check of vehicle dynamics. *2021 IEEE 25th International Conference on Intelligent Engineering Systems (INES)*, 31–36. Budapest, Hungary. <https://doi.org/10.1109/INES52918.2021.9512897>

LSTM-Based Forecasting and Sensitivity Analysis of Yaw and Roll Rates in Automotive Systems

- P5** János Kontos, László Bódis, Ágnes Vathy-Fogarassy (2025). Sensitivity analysis of Long Short-Term Memory-based Neural Network Model for Vehicle Yaw Rate

Prediction. *Sensors* (Q2), 25 (5), 1363. <https://doi.org/10.3390/s25051363>

P6 János Kontos, László Bódis, Ágnes Vathy-Fogarassy (2023). Prediction for Future Yaw Rate Values of Vehicles Using Long Short-Term Memory Network. *Sensors* (Q2), 23(12), 5670. <https://doi.org/10.3390/s23125670>

P7 János Kontos, László Bódis, Ágnes Vathy-Fogarassy (2024). Forecasting Roll Rate for Sensor Plausibility Check in Off-Road Vehicle Conditions. *2024 IEEE 3rd Conference on Information Technology and Data Science (CITDS)*, 1–6. Debrecen, Hungary. 10.1109/CITDS62610.2024.10791355

MTMT profile

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